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NEW METHOD OF CALCULATING CORRECTIONS OF TEST RESULTS IN A LOW-SPEED WIND TUNNEL (BLOCKAGE CORRECTIONS AND WALL CORRECTIONS)

J. C. Vayssaire

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NEW METHOD OF CALCULATING CORRECTIONS OF TEST RESULTS IN A LOW-SPEED WIND TUNNEL (BLOCKAGE CORRECTIONS AND WALL CORRECTIONS)

J. C. Vayssaire

Abstract. Demonstration of how empirical formulas, which serve to determine the scales of models in low-speed wind tunnels, are inadequate and lead to the use of small models in large test chambers. Two types of corrections are proposed (blockage corrections and wall corrections) to obtain uniform results from models or half-models of large size in relation to the test chamber. A number of studies dealing with blockage corrections are analyzed. The essential concepts relating to wall corrections are reviewed and further developed. Currently used blockage correction formulas are presented, and some examples of wall corrections are proposed. The study is illustrated by some test results.

Foreword /55*

Confronted by a certain degree of scattering of test results provided by low-speed wind tunnels, chiefly with a view to investigation of centers or high list coefficients, Mr. H. Deplante, General Technical Director, and Mr. O. Monod, Chief of the Aerodynamic Testing Division of Marcel Dassault Aircraft, have suggested, in February 1966, the undertaking of the present study. Their report was made during a meeting of the Commission of Aerodynamics of the AFITAE.

During this meeting, Mr. J. Brocard recollected that the semi-guided rectangular sections (like those of the Breguet wind tunnel) require wall corrections so low that they can almost be disregarded. This quality, quite recently confirmed by several tests of models of Dassault aircraft, led to the recollection of ideas held by Professor A. Toussaint, as well as formulas and results relating to these corrections made before 1940.

It will also be noted that the theoretical corrections shown in the following pages can be swiftly accomplished directly from the output of

*Numbers in margin indicate pagination in foreign text.

measuring chains of wind tunnels, using computers.

It was therefore absolutely necessary to translate the correctional formulas into machine languages. This, furthermore, will improve precision in the determination of certain corrective terms.

Summary

Wind Tunnel Interference at Low-Speed

Part one shows how the empirical formulas used to specify the scales of models in low-speed wind tunnels are inadequate and lead to the use of small models in large test sections.

Two types of corrections are proposed in this case: blockage corrections and wall corrections, in order to provide uniformity of experimental results produced using models or half-models having large dimensions with respect to those of the test section.

Part two analyzes various works relating to blockage corrections. These corrections essentially consist in natural scale correction of the reference dynamic pressure, hence velocity.

Part three takes up the essential ideas relating to wall corrections, /56
then further developed. The latter are used to correct the reference velocity in direction.

Part four discusses proposals for blockage correction formulas now in use and some examples of wall corrections are given. These examples relate to testing of models in a guided circular section and half-models placed in front of a panel located in a guided circular section.

Part five of this study is illustrated by some test results from Avions Marcel Dassault models corrected according to the method studied. The relative importance of various corrections is detailed.

In conclusions, the developmental potential of this study and remaining problems are discussed.

Key bibliographical references are listed. Some minor references are mentioned in the text.

Part One: General Comments

1.0

It is still conventional at the present time to assume that, in order to produce valid results, i.e. requiring only slight corrections, it is necessary to use small models in large wind tunnels.

The wall corrections and the blockage corrections are therefore reduced to a minimum. Blockage corrections are sometimes even disregarded.

1.1

In this way, as a general rule, the span of a model of a straight wing or that of a complete airplane should not exceed 75% of the width of the test section. Stewart, among other writers, has mathematically demonstrated this rule by calculating the velocities induced by the walls according to the span of a straight wing placed in a test section with circular cross section [1].

In a free circular test section, a wing whose span is too large behaves as if it had a twist greater than reality and the results are optimistic with respect to flight. The contrary situation occurs in the case of a guided circular test section.

1.2

Nevertheless, this rule has been found inadequate in the case of the delta wing or swept back wing. The surface S of such airfoils with respect to cross section C of the airway of the test section plays a great role. It is proposed in this case, in order to produce suitable results, to use rules such as:

$$\frac{S}{C} < 0,085 = \frac{1}{12}$$

or better /57

$$Cz_{max.} \cdot \frac{S}{C} < 0,13$$

TABLE OF SYMBOLS

C =	Cross section of airway in the test section.
$C = S_0$	(In the case where the test section is occupied by a complete model in the absence of panels or platform).
$C < S_0$	(Case of the half-model with wall--see Figure 4).
Cm_u	Coefficient of uncorrected pitching moment.
Cx_d	Coefficient of drag of separations.
Cx_u	Coefficient of uncorrected drag.
Cz_u	Coefficient of uncorrected lift.
Cm	Coefficient of corrected pitching moment of the blockage.
Cx	Coefficient of corrected drag of the blockage.
Cz	Coefficient of corrected lift of the blockage.
Cm_c	Coefficient of entirely corrected pitching moment (blockage and walls).
Cx_c	Coefficient of entirely corrected drag.
Cz_c	Coefficient of entirely corrected lift.
D	Equivalent diameter of the maximum fuselage cross section.
L	Length of the fuselage.
R	Radius of a circular test section.
S	Reference surface of the model. Total surface of a complete model. Surface of the path airfoil (case of the half-model).
S_e	Surface of the horizontal stabilizer, including the part in the fuselage.
S_0	Cross section of the test section = πR^2 in the case of a circular test section.
V_0	True "infinity upstream" velocity.
Vm	Volume of the model.
b	Span of a half-model.
$2b$	Span of a complete model.
c_b	Chord of the wing tip.
c_o	Chord on the axis of symmetry of the wing.
c_r	Reference chord.
d	Distance from the panel to the center of the circular test section.
e_m	Maximum thickness of a profile.
i	Incidence of the model.
j	Side slip angle of the model.
$\bar{l}$	Main aerodynamic chord.
$\bar{l}_a$	Main aerodynamic chord of the wing, defined by

$$\bar{l}_a = \frac{2}{3}\left(c_o + c_b - \frac{c_o \cdot c_b}{c_o + c_b}\right)$$

TABLE OF SYMBOLS (CONT'D)

l_a	See Figure 7.
l_e	See Figure 7.
l_G	See Figure 7.
q	Dynamic air pressure.
u	Induced axial velocity.
w	Induced vertical velocity.
x_G	See Figure 7.
ΔCm_a	Correction of airfoil pitching moment.
ΔCm_e	Correction of pitching moment of horizontal stabilizer.
ΔCx	Correction of walls relative to drag.
ΔCx_g	Correction of drag coefficient owing to static pressure gradient of the wind tunnel.
ΔCx_s	Correction of drag coefficient owing to slip stream gradient.
Δi	Correction of walls relative to incidence.
δ	Coefficient of correction of walls corresponding to the mean value of the angle induced in span taken according to the line located at the quarter point of the chords beginning from the leading edge.
$\lambda = 4b^2/S$	Geometric elongation.
ρ	Specific gravity of the air.
~~τ~~	~~Coefficient of development of the angle induced by the walls accord-~~ ing to a direction parallel to the longitudinal axis of the wind tunnel.
$1 + 2\varepsilon$	Coefficient of correction of dynamic pressure.

Subscripts

a	Relating to the wing.
c	Entirely corrected.
e	Relating to the stabilizer.
f	Relating to the fuselage.
G	Relating to the center of gravity position.
u	Uncorrected.
δ	Relating to the correction of walls defined by the coefficient δ.

1.3

Our goal is therefore to make uniform those wind tunnel results produced beginning from models of a same aircraft carried out using different scales and tested in various types of test sections by applications of relations of suitable corrections.

In the present state of the art, we have ascertained that the proposed relations warrant values of:

$$\frac{S}{C} \cong 0,2 = \frac{1}{5}$$

or even

$$Cz_{max.} \frac{S}{C} = 0,37$$

1.4

These are double corrections: blockage corrections as well as wall corrections.

The result from mathematical developments consisting in the substitution for the flow around the wing or a streamline body of a system of vortices, doublets, sources and walls.

A slip stream likewise can be replaced by a source so far as it is possible to depict an aircraft by "artificial" mathematical means presenting problems whose solutions become more exact and precise as the simulations become closer to reality, hence more complex calculations.

In addition, the wind tunnel walls complicate these calculations still more, since it is possible to simulate their presence by substituting for them infinite rows of pictures of vortices, sources and sinks defining the wing or the aircraft. The effects of this system of pictures on the model /58 are the same as those of the walls.

Note that the walls of the wind tunnels are free or guided requiring a definition of conditions at the boundaries.

At the level of exploitation of the tests it is absolutely necessary to determine precisely some of the geometric data and, in addition, to make supplementary tests passing beyond the scope of the wind tunnel testing program heretofore strictly limited to the aircraft program. These supplementary tests are necessary in order to define some corrective terms with precision.

1.5

These corrections therefore result from the concept of "induced velocities: caused by the model in the presence of walls: axial induced velocities insofar as concerns "blockage," vertical induced velocities in the so called "walls" case.

In reality, these induced velocities are applied on the model and result from rows of pictures of special features replacing the wing or aircraft and which are substituted for the walls.

Furthermore, we shall no longer consider these induced velocities as conceding a constant mean value at right angles to the bearing line perpendicular to the direction of the "infinite downstream" velocity which is substituted for the airfoil.

This constant mean value results from theoretical calculations based either on the hypothesis of an elliptical distribution or on the hypothesis of a constant distribution of the lift in span. These two calculation modes provide, furthermore, quite uniform results. (4")

We shall then consider these induced velocities in their development according to directions parallel to the longitudinal axis of the test section from the bearing line as far as downstream infinity.

1.6

The components needed to set up these corrections have essentially been extracted from various reports made in aerodynamics published both in France and abroad (Germany, England, Japan, USA) before the Second World War by many scientists, or immediately following the latter.

They were analyzed, collated, then studied together for interrelationships in order to define a method for correcting raw test results made in a low velocity wind tunnel operated by Avions Marcel Dassault. It was found possible to generalize the study for a better interpretation of our own studies in experimental aerodynamics.

At the present time, the corrections of walls, improved ones, involve the incidence (if necessary the lift coefficient), the drag coefficient and the coefficient of pitching moment or as the corrections of blockage are applied to the six components (at the same time taking some precautions insofar as the three components of the lateral are concerned).

This constitutes a considerable development from the time when Prandtl and, above all, Glauert took them under consideration and summarized them [2].

1.7

The applications of these double corrections to the raw data are subject to two controls:

The raw data have already been corrected for the ascendency of the test section and the various interactions of the components as well as interactions of supports. These supports create not only additional harmful drags but also effects on the lift and even the pitching moment of the model [3].

The raw data, in the form of dimensionless coefficients, have been related to a dynamic reference pressure, i.e. to a "infinite upstream" true velocity which is independent from the incidence or deflection of the flaps, for example.

This true velocity results from prior calibration in the wind tunnel. It is measured by a Pitot tube placed in an advantageous position or else given an experimental factor, or compensated by any other suitable means.

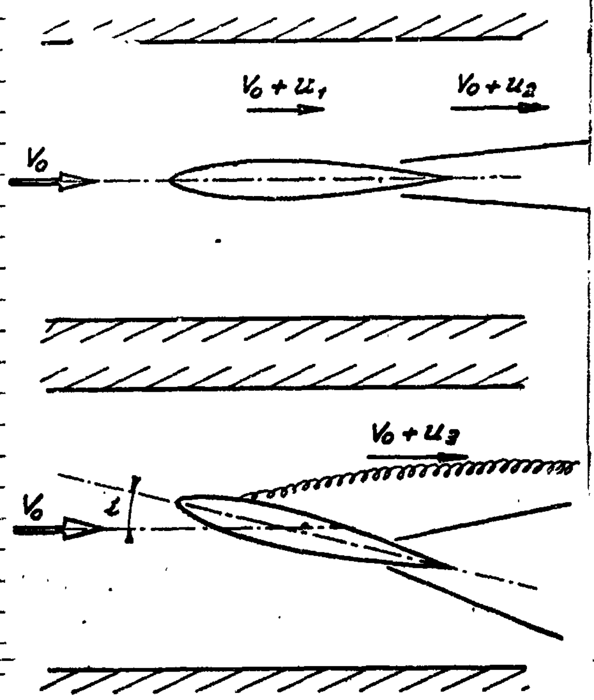
2.0 /59

The blockage corrections are the first ones which should be considered since they essentially correct the dynamic reference pressure to which are related the raw coefficients measured by the wind tunnels. These corrections are essential and important in the guided test sections.

2.1

These corrections include three terms corresponding to the volume of the model, to its slip stream and to its separations.

Definitions of Blocking



The Airway Cross Sections Decrease

Owing to { the Model, the Slip Stream, Separations }

Three Causes of Increase in Velocity

Figure 1. Definition of Blocking.

It may easily be understood that each one of these components contributes to the reduction of the cross section of airway of the experimental test section. The result is that there is, owing to continuity of flow, an increase in the true "infinite upstream" reference velocity (Figure 1).

In addition, the increase of velocity in the main flow contributes to a reduction of static pressure and an increase in the thickness of the boundary layer on the model. This (4'') ~~explains not only an increase~~ in velocity but the creation of a static pressure gradient which overlaps the static pressure gradient characteristic of the test section. Each one of the gradients contributes to the creation of an undesired drag. It is therefore advisable to deduct from the total drag these two drags that can be classified among the blockage corrections.

Glauert has done a good job of specifying and summarizing the basic calculations connecting a pressure gradient or velocity to the undesired drag resulting from them [2].

We shall confine ourselves, in this study, to the correction of this component only, although one gradient can have an interaction with all six components of aerodynamic stress and moment (see A.R.C.R. and M 1166 and 1909).

2.2

The origin of calculations relating to blockage corrections appear to go back as far as the works of Lock (1929) and as continued by Glauert.

Lock was only interested in the calculations of volume blockage in the two and three dimensional system. In the two dimensional system, in a rectangular test section with height H, there already appear terms such as $(em/H)^2$ and such as $(1/C)^{3/2}$ in the case of the three dimensional system [4]. Indeed, these are relations which have been exploited and further developed in recent times.

As a matter of fact, let us recall that Glauert borrowed largely from the relations of Lock at the same time greatly simplifying their mathematical development. He likewise attempted to proceed further by proposing empirical relationships of corrections of blockage, slip stream and vortex originated separations [2].

2.3

In England, Thom (1943) calculated the "volume blockage" and "slip stream blockage" with application to the plane flow using the case of a three dimensional model placed in a rectangular test section [5].

Thom replaced the profile by a distribution of lines from sinks and sources.

The slip stream is depicted by a source placed at the trailing edge, this concept having been proposed at various times by Prandtl [6]. However, in the wind tunnel, the source should be accompanied by a sink of equal intensity located quite far downstream. Maskell (1965) supplemented this work by specifying a term for "blockage of separations" [7]. This term, produced beginning from a skillful mix of theories and experimental data taken from British reports published during the years, is a function of the elongation of the airfoil.

2.4

In the United States, Allen and Vincenti (1944), have proposed, for the plane flow, correction formulas which are especially suitable and quite complete [8]. Their volume blockage correction very exactly connects with those of Lock but it introduces terms which were calculated for the profiles of contemporary wings. Their slipstream blockage correction is identical to the one proposed by Thom.

Then Herriot (1950), taking up again the working bases from Thom and recalling those of Lock, has calculated the "volume blockage" generally for rectangular test sections and for guided circular test sections. He then brought into play the span of the model and the diameter of the fuselage [9]. In a case of the slipstream blockage, Herriot reuses the formula of Allen and Vincenti.

2.5

In summary, we have ascertained that the "slipstream blockage" function of the drag of the model, variable with the incidence, has an identical shape in the case of the authors mentioned above. This term is usable no matter what may be the cross section of the experimental test section.

On the other hand, we have preferred the "volume blockage", constant term, of Thom because more simply, perhaps less detailed than that of Herriot but finally applicable no matter what may be the cross section of the test sections. In addition, this term has been found to be usable in the half-model tests with the wall located in a guided circular test section.

In reality Thom provides with the products of factors calculated by Herriot and which define on one hand the geometry of the test section and on the other hand the span of the wing or diameter of the model fuselage, the constant values 0.9 and 0.96 as can be seen in section 4.1.1.

These values include most common cases without contributing appreciable errors, as can be seen in the following table set up for some models of Marcel Dassault Aircraft.

We should like to note that the last reports from NASA published in /60
1967 or 1968 still refer to the Herriot report when blockage corrections are carried out, thus reassuring us of the still current validity of the documents which we have consulted.

VOLUME BLOCKAGE--TERM 1 + A
(SEE SECTION 4.1.1)

	S_5 Toulouse 2R=4,25 m		S_2 Chalais 2R=3 m	
	THOM	HERRIOT	THOM	HERRIOT
Mirage IV			1,0063	1,00531
Mirage III V			1,00371	1,00294
Mirage F2	1,00368	1,00296	1,0105	1,0085
Mirage G	1,0031	1,0025	1,00878	1,00724

We have therefore used the terms: "volume blockage" provided by Thom; "slipstream blockage" provided by Thom or Herriot[1]; "separation blockage" provided by Maskell.

The characteristic relationships valid for three dimensional testing are provided in part four of this study.

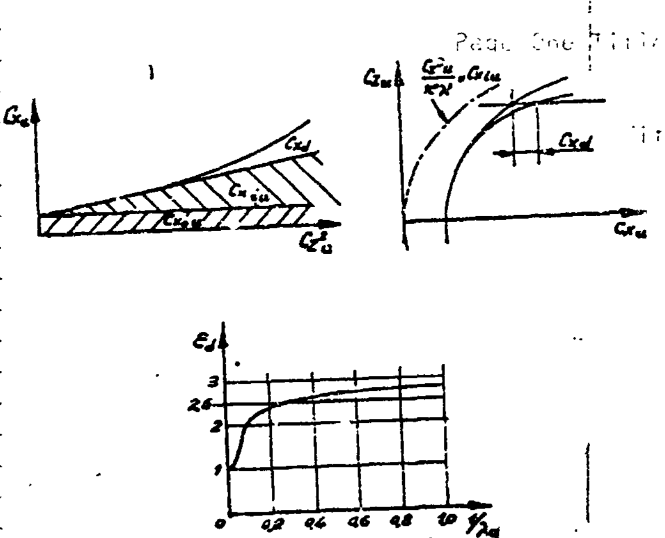
2.6

In the case of a model having a wingspan of given elongation, to obtain as a function of the incidence, the coefficients of drag and separation characterizing the corresponding blockage term, is rather difficult. It is possible to use the graphic method by plotting Cx_u as a function of CZ^2_u (Figure 2). Nevertheless, it appears preferable to go through the intermediate step involving search for the induced polar unit or even better the parabola which is calculated and mixed with the experimental polar unit on the large CZ_u area (Figure 2).

Research of the parabola by the method of least squares applied to experimental points CZ_u and CX_u is possible by machine.

Nevertheless, in order to obtain a good precision, it is important to take measuring points closer together along this parabola and even, if possible, to consider the parabola as a whole. In this case, it is found suitable to carry out testing using the incidences found in the environment. Thus, for example, during the study of high lift wings, measurements using

[1] This term is found as early as 1940 in Germany. See Wieselsberger and Gothert, L.G.L., Report 127.



λ_α = Geometrical Elongation of the Wing

Figure 2. Definition of Separation Drag.

high incidences are begun in order to satisfy the needs of the aircraft's manufacturer, but it is necessary to perform tests using low incidences, even negative incidences in order to specify the corrective terms for the wind tunnel.

This method has been developed by the planning office of Avions Marcel Dassault, at Saint-Cloud. It is proposed for use by offices involved with calculation and analysis of wind tunnel testing.

This term for correction of separations is supplied in a completely general way. It may be used, for example, in the case of slender wings as soon as the apex vortex appears as well as in the case of all vortex flows provided that they originate rather far upstream on the trailing edge. The induced parabola is then determined using a reduced area of low incidences.

In the lateral case, as noted by Mr. Taurel, Chief of the Aerodynamic Group at CEAT, separations can originate with low incidence but with strong sideslip. The understanding of the term separation blockage, in this case, is then determined beginning from the induced parabola Cy_u, Cx_u graduated as an angle of sideslip j^o.

2.7

When the supports of models, such as mass and fairings, are located in the test section, it is important to take into account by their volume and drag--two constant terms. It is sufficient to merely increase the constant term "volume blockage" of the model by a certain percentage.

2.8

Let us conclude with the fact that it is advisable to distinguish between the "corking effect" and "blockage". The corking effect is caused by the loss of load created by the model in the flow inside the wind tunnel. There results from this a reduction of velocity, quite visible with increase of incidence, which is recorded by the Pitot tube measuring the "true upstream infinite" velocity. In this case the blockage is an increase in velocity around the model and may be calculated.

2.9

We have just examined the case of guided test sections.

In the case of the free test section, the blockage directions can be practically disregarded.

As a parenthetical note, let us nevertheless recall with Lock [4] and Glauert [2] that in this type of test section there is a corrective term for volume. This term is equal to that which is calculated for the guided test section of the same geometrical shape. However, with a free test section, it should be multiplied by -1/2 in the case of two dimensional tests and by -1/4 for three dimensional tests. Therefore, these very small corrections can be disregarded and we can, nevertheless, note the appearance /61
of a negative sign.

In the period 1939-1941, the Germans, with Goethert and Kuchemann, became interested in this type of test section from the compressible aspect point of view, presumably owing to the small size of their blockage corrections, chiefly those arising from the slipstream which can be freely expanded.

They did, however, place much emphasis on the blockage term owing to the model volume which assumes a rather large importance in compressible flows and insofar as calculations can be made in the domain of validity of the Prandtl-Glauert rule, i.e. before the appearance of a local sonic velocity.

Nevertheless, the separations remain and, returning to the incompressible aspect, it can be asked, but by the mere consideration of a "dead zone" behind the model, if the blockage resulting from this does not behave like a pseudoblockage of volume (see ARC R and M 3120), additionally connected to the turbulence of the wind tunnel and the roughness of the model.

The same problem likewise remains in the case of semi-guided test sections.

Nevertheless, beginning from the work of Maskell, it is possible to deduce a method capable of experimentally determining the coefficient characterizing the blockage term owing to separations in all cases of test sections.

Part Three: Wall Corrections

3.0

Since the blockage corrections have provided the raw aerodynamic coefficients their exact values, it is advisable then to make application of wall corrections.

3.1

The problem of these corrections was investigated and solved by many scientists before the Second World War.

In plane flow, the profile is replaced by a certain number of particular features which are generally arranged at the quarter point of its chord with respect to the leading edge and the stresses of test section limitation by an infinite row of pictures of these special features with the same orientation in the case of the free test section and with an opposite orientation in the case of the guided test section. The induced velocities are then calculated using these pictures at the point located three quarters along the chord of the profile or even, at its middle point, at the same time then taking into account the curvature of the airflow caused by these velocities. These various methods have been reported by Prandtl, Glauert, Pistolesi, Sasaki, Rosenhead, Tomotika, Toussaint and Goldstein.

The corrections in the three dimensional flows consist, by assuming either a constant distribution, or an elliptical distribution of the lift in span, in order to calculate the induced velocities w by an infinite system of vortices, pictures of marginal vortices of the actual wing, at right angles from the line located at 25% of the chords behind the leading edge.

By taking for these velocities induced in span a constant mean value, there is found the well known conventional diagram of simple wall corrections involving first incidence and then drag.

These corrections have been found inadequate for wings which are small in size, straight or have a slight sweep back of the leading edge, a great elongation or even a moderate elongation.

Indeed, these induced velocities are evolutional on one hand in span, on the other hand according to directions parallel to the longitudinal axis of the wind tunnel test section.

These considerations become absolutely necessary for study of the behavior of wings with slight elongation, i.e. for delta wings or for wings which have a rather large sweepback. Naturally, they are still useful in the case of aircraft models which have horizontal [48] stabilizers.

In the first analysis, without taking into consideration the development in span of induced velocities, we shall only use the value of this velocity at right angles to the "mean aerodynamic chord" of the airfoil, while still evaluating its variation according to this chord.

Certainly, by acting in this manner, we are disregarding wall corrections relative to the lateral: roll correction or roll. However, we shall reveal additional wall corrections relating to the profile whose chord is confused with the mean aerodynamic chord and identical to those that could be found for this profile tested in a plane flow; i.e. supplementary corrections for incidence, lift, pitch and, if necessary, drag.

These corrections correspond to a linear development of the induced velocity according to the profile chord, hence to a camber of the circular type of aerodynamic field according to the longitudinal axis of the test section.

This camber, or curvature, is extended to infinity downstream and interacts with the horizontal stabilizer which is responsive to suitable corrections.

3.2

Emphasis should be placed on the fact that the angles induced by the walls, resulting from the composition of vertical velocities induced with the "upstream infinite" true velocity, are overlapped with the induced angles of the Prandtl theory relative to wings of finite span located in an unlimited environment. They may likewise add to the deflection angles caused by the airfoil and which can be found at right angles to the horizontal stabilizer.

Before carrying forward the development of what has been described above, it is worthwhile to review some basic data.

3.3 Review of Concepts Concerning Wall Corrections /62

3.3.0

In the case of straight wing with a S surface located in a completely guided test section with a cross section So, the vertical induced velocity w, as seen by the pictures, is directed upward. The angle measured in the wind tunnel is therefore too small. It should be increased by:

$$\Delta i\delta = \frac{w}{V_o} = \delta \frac{S}{S_o} Cz.$$

In the case of a free test section, the induced velocity w is directed downward. The measured angle is therefore too large. The coefficient of correction δ is negative.

3.3.1

The determination of the absolute value of the coefficient δ can produce, on a preliminary basis, some surprises. It would appear wise to review a theorem ascribed to Glauert [10]:

"The wall corrections that should be applied to a wing with small span, located in a free test section of any geometrical shape whatsoever, are of the same magnitude but with a sign the reverse of those that should be applied to the same wing, pivoted 90°, but located in a guided test section of the same shape."

Figure 3 illustrates this theorem by taking as examples four types of test sections: circular, square, rectangular and elliptical.

It is clear that, in the case of square or circular test sections, the preceding theorem is valid without causing the wing to pivot by 90°, since these are symmetrical test sections.

3.3.2 Case of Elliptical Test Sections

Let B and H be the respective size of the width and the height of the ellipse.

In the case of a wing with a span 2b equal to the focal distance, whose distribution of circulation is elliptical and placed symmetrically with respect to the two axes, the coefficients are very closely provided by the formulas:

$$\delta = \frac{1}{4} \cdot \frac{H}{B+H} \text{ for the guided test section,}$$

$$\delta = -\frac{1}{4} \cdot \frac{B}{B+H} \text{ for the free test section.}$$

Therefore, for a same value of the ratio B/H greater than 1, the elliptical guided test section is responsive to a smaller correction than that corresponding to the free elliptical test section.

A rotation of 90° of the wing thus demonstrates the Glauert theorem. In addition, in the case of the circular test section with a radius R in which

$$R = B = H$$

and, in a case of a wing with an infinitely small span, the following is certainly true:

$$\delta = 1/8 \text{ in the case of the guided test section,}$$
$$\delta = -1/8 \text{ in the case of the free test section.}$$

Wall Corrections?
Reverse Sign. Same Absolute Value.

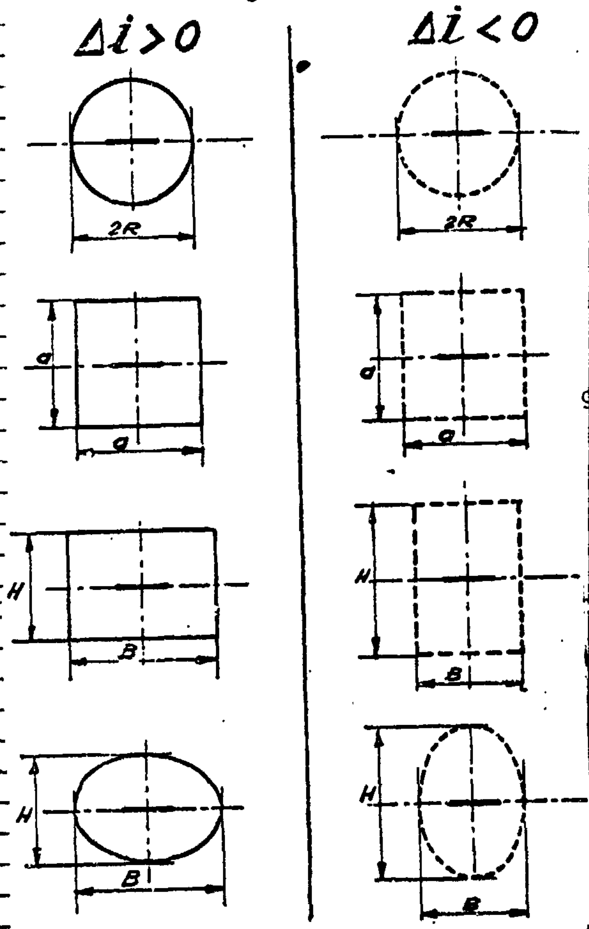


Figure 3. Guided Test Section - Free Test Section. Glauert Theorem.

3.3.3

The following are the names of some of the scientists who, between the two World Wars, treated the problem of wall corrections: Glauert, Terezawa, Theodorsen, Rosenhead and P. de Haller.

We shall use chiefly: Prandtl in the case of circular test sections [11]; Toussaint in the case of rectangular test sections [12] and [13]; and Sanuki in the case of elliptical test sections [14].

We shall likewise mention the works of Malavard. This writer takes up wall corrections in their entire system by the method of rheoelectric analogies [15]. We should not forget the synthesis work of Chaffois [16].

3.3.4

The basic calculations for the corrections are accomplished by assuming the wing located in the center of the test section, generally the case in testing.

It is therefore possible to consider the case in which the wing is clearly above or below this central position.

The correction calculations show that the greater the distance from the center of the wing going towards the upper part of the test section, the more the corrections increase [17], for example.[2]

3.3.5

The free test section, the longitudinal position of the wing with respect, on one hand, to the collector output, on the other hand, to the input of the diffuser has some interest.

With a plane current Toussaint [13], page 304, and Sasaki [16], pages 27-28, have dealt with this problem. For the three dimensional test, it is advantageous to consult [21].

In a general way, it appears that the wing should be located, with respect to the output cross section of the collector, at a distance equal to a value included between half of the height and the total height of this cross section.

3.3.6

Let us comment on corrections having to do with half-models placed against a panel.

When the panel consists of one of the walls of a rectangular test section, [22] can be consulted.

When the panel is located in a guided circular test section, the works of Kondo in [23] can be used.

From the comparison between the values of the δ coefficients resulting from the calculations of Sanuki dealing with elliptical test sections (summaries in the Kondo report) and those produced by Kondo relating to circular test sections when limited by a panel, we are able to conclude that: from

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[2] This finding should be reconciled with calculations of corrections relating to tests of models in the presence of the ground (ground-interaction). Indeed, the more the model comes closer to the platform representing the ground the more the corrections decrease eventually becoming negligible when the model simulates taxiing on the ground [18, 19, 20, 23], for example.

-the aerodynamic viewpoint, a circular test section with a radius R limited by one panel situated at a distance d from the center of the test section is perceptably equivalent to an elliptical test section having as its minor axis 2R and has its major axis 2(R + d) (Figure 4).

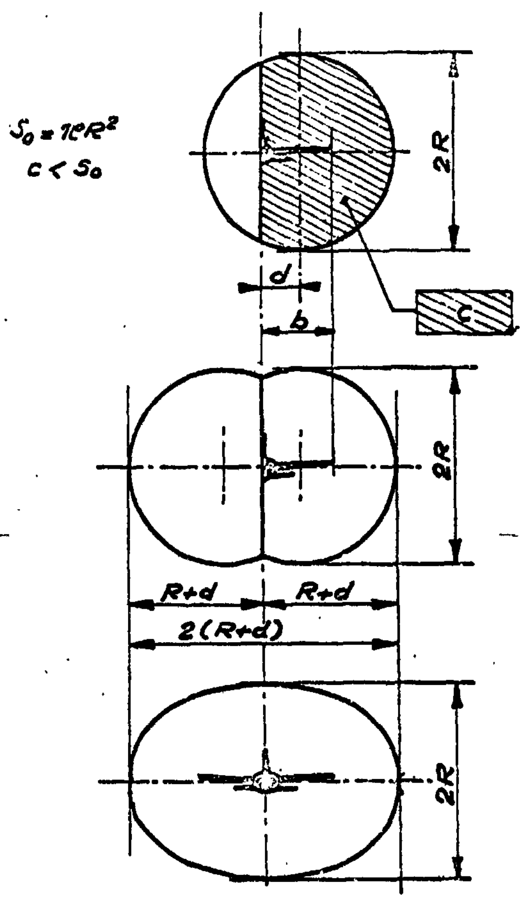

Figure 4. Half-Model With Wall. Circular Test Section. Elliptical Test Section.

This concept of equivalency may be generalized. In this way, a half-model placed against the vertical wall of a guided rectangular test section with a height H and width B may be assimilated to a complete model located in a test section with the same height but whose width is 2.B (see [22], p. 8). In addition, [22] anticipates [34] and [35] mentioned below.

(4'')

3.3.7

These various basic concepts further demonstrate their importance by recalling the concern of some scientists and the requirement laid on by engineers for the production of test sections in which wall corrections would be 0, or at least negligible. It is advisable to remark that this idea was particularly developed in France by Toussaint.

It may be imagined, beginning from considerations concerning free test sections and guided test sections, that it is possible to set up semi-guided test sections, the purpose of research on corrections having one imposed value. We can likewise reduce these corrections to zero with a suitable proportion of guided walls with respect to free walls.

Figure 5 illustrates this investigation. /64

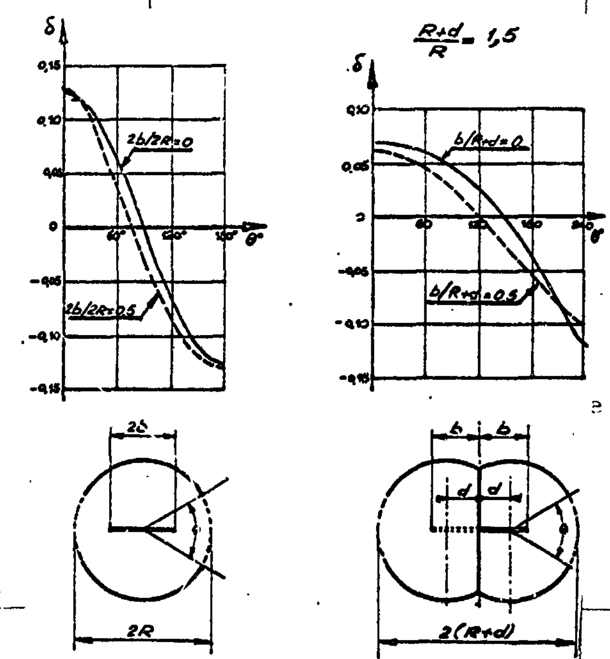

Figure 5. Semi-Guided Test Sections.

The curves corresponding to the circular test section are extracted from the works of I. Tani and M. Taima [24] and summarized by Kondo. These discussed the same problem in the case of half-models at the wall [25]. Malavard also discussed this problem generally in the case of circular or elliptical test sections [15].

(4) But from 1935 on, Toussaint noted the importance of the floor and ceiling in the case of semi-guided rectangular test sections.

The curves provided by Theordosen have already been explicit [26]. Nevertheless, we prefer those plotted beginning from the works of Toussaint (Figure 6, [12]). Toussaint wrote at a time when such test sections were supposed to have a double advantage: corrections practically zero and easy design for private industrial laboratories [13], page 295. Under these conditions, two wind tunnels were produced having such test sections: first of all, wind tunnel number 2, low velocity, of the Institute Aerotechnique of Saint-Cyr School (B = 2.10 m and H = 1.80 m) then, in 1939, the Breguet wind tunnel, located at Velizy, (B = 3.80 m and H - 3.07 m).[3]

[3] The Breguet wind tunnel was constructed with the backing of M. J. Brocard and completely designed by M. Gruson, engineer at the Institute Aerotechnique of Saint-Cyr.

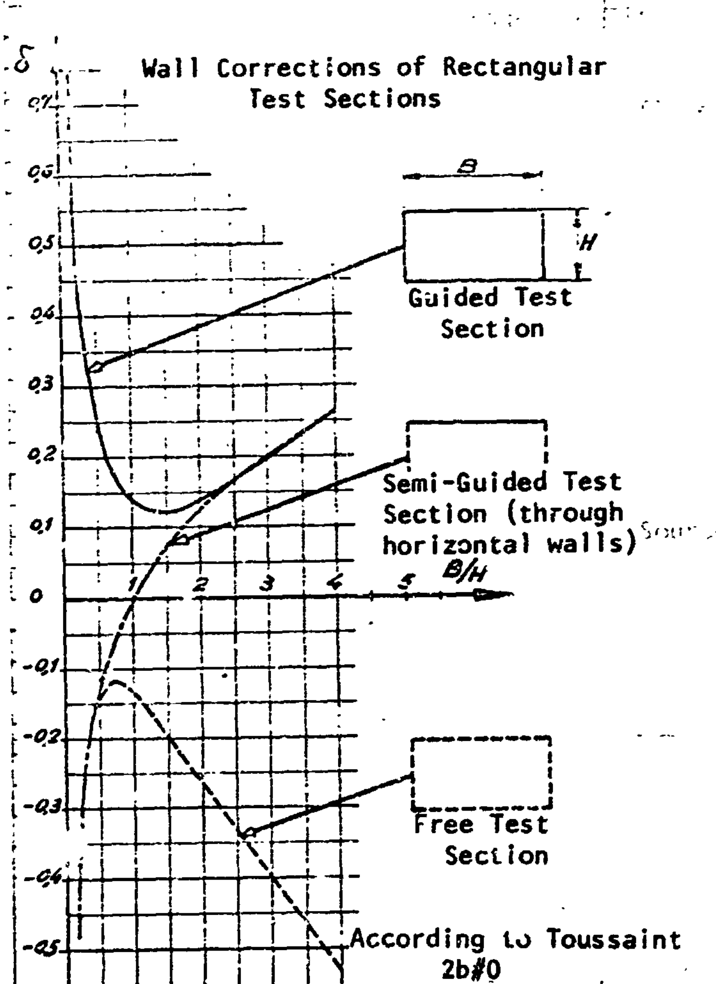

Figure 6. Rectangular Test Sections (Toussaint).

In this latter wind tunnel, the corrections are zero, when $2b/B \cong 0.57$, or $2b = 2.16$ m since $B/H = 1.24$, since B and H respectively designate the width and height of the rectangular test section.

3.4 Development of Wall Corrections. Evolution of Induced Velocities.

3.4.0

The corrections previously shown are based on the concept of induced angle $\Delta i_\delta = w/Vo$ through the walls, localized at the quarter point of the chord of the right wing or the bearing line and using the hypothesis that the value of w remains constant.

3.4.1

Indeed, w evolves in span. Nevertheless, as a first approximation, there still may be used for w a constant value, one which is perceptibly equal to its mean value in span and which will be located at the quarter point of the mean aerodynamic chord of the airfoil.

Subsequently, consideration is given the evolution of this vertical velocity induced according to this chord. This evolution is linear. It therefore generates a curve, or camber, of the circular type of airflow around the privileged profile whose chord is n[illegible] with the mean aerodynamic chord.

In this way, supplementary corrections appear which we can determine by using some of the hypotheses which have been offered for the calculation of corrections of walls relating to profiles tested in a plane flow.

By considering the velocity induced in the middle of the mean aerodynamic chord la with respect to the one which is at the quarter point of this same chord, a determination may be made of the corrections for list, pitching moment and incidence, taken therefore as a function of la with a line drawn above $\overline{la}/4$. This follows the original meaning of Glauert [2].

Nevertheless, it is possible to disregard the lift direction and carry it over entirely to the incidence by doubling its preceding value.

Distance la/2 is revealed and the hypotheses of Pistolesi are used in this case, calculating the induced velocity at three quarters of the chord of the profile [27].

Furthermore, since the effect of the wall is to introduce around the wing a circular camber of the test section, in agreement with the theory of ~~fin profiles, the effective angle of incidence is certainly the angle located~~ (4'') at the three quarters point of the chord.

3.4.2

In addition, following a direction parallel to the longitudinal axis of the wind tunnel test section, the vertical velocity induced by the walls evolves far downstream from the airfoil.

Such an evolution had already been offered by Glauert so as to correct for measures of deflection at right angles from the horizontal stabilizers [28].

More recently, Heyson, confronted with the requirements of V/STOL aircraft, well described the problem of pitch corrections [29].

Heyson proposes two methods. On one hand, he considers a correction /65 based on a rotation of the airflow, rotation defined by the difference of angles induced between the horizontal stabilizer and the airfoil.

On the other hand, he proposes a simple correction of pitch moment, correction which only involves the contribution of the horizontal stabilizer at this instant ([29], p. 11, formula 16). This latter viewpoint supports the method which we have already used and the correction relation which we have calculated elsewhere.

Consistent with the preceding comments, it is suggested to use the angle induced at three quarters of the mean aerodynamic chord le of the horizontal stabilizer. There should also more especially be considered the mean aerodynamic chord of the part of the stabilizer outside the fuselage, since the angle induced by the walls, well defined on the lift surface, is undefinable on the part screened by the fuselage, and above all, when the stabilizer is located against the sides of the latter.

If necessary, a stabilizer which is located quite high on the fin can be treated as an isolated airfoil.

3.4.3

~~We are therefore going to provide a general idea of the development of~~ the calculations.

When at right angles of the bearing line: $\Delta i_\delta = \frac{w}{V_o} = \delta \frac{S}{S_o} Cz$, at a distance x = 1 downstream from this line, w has changed and has become w + τw, Such that:

$$\Delta i = \delta (1 + \tau) \frac{S}{S_o} Cz$$
$$= \Delta i\delta + \tau . \Delta i\delta$$

This evolution of the τ coefficient, parallel to the longitudinal axis of the wind tunnel, has been calculated in the case of circular and elliptical test sections by Miss Lotz [30].

Having compared a half-model with wall in a circular guided test section to a complete model in an elliptical test section, the work of Miss Lotz has been especially valuable and it will be used in the applications proposed in parts four and five.

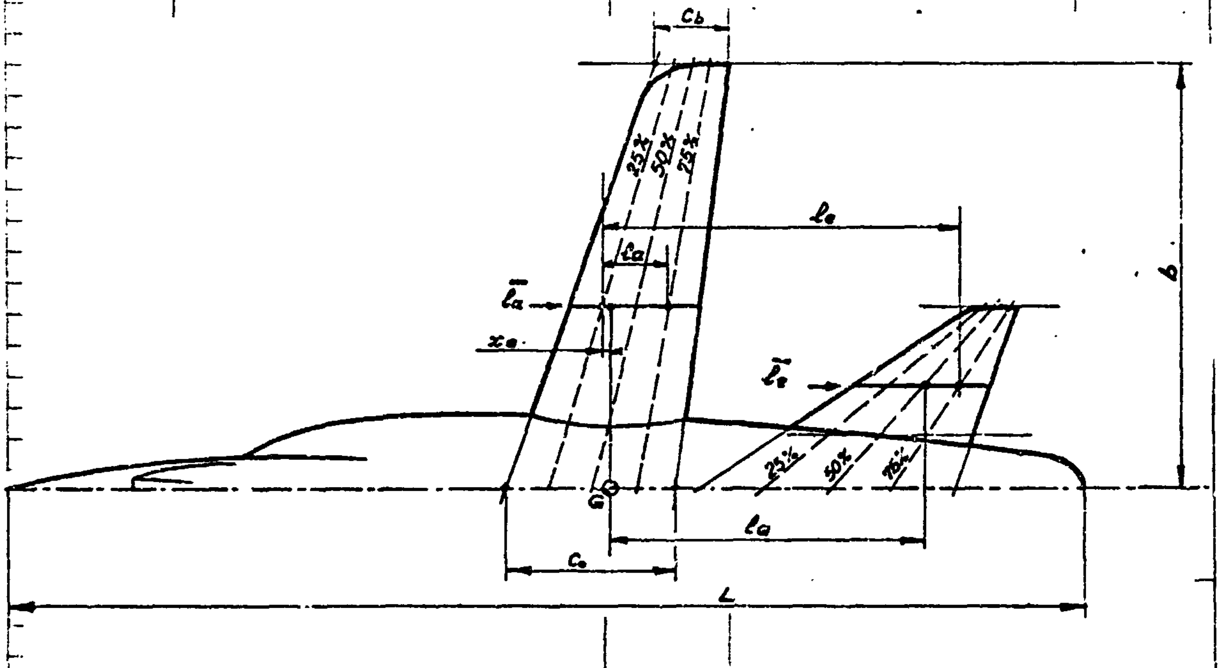

Figure 7. Definition of the Notations.

τ is a function of distance l related to 2R or to 2(R + d) (see Figure 4).

Insofar as concerns the rectangular test sections, Silverstein and White have calculated τ as a function of distance l related to width B of the test section [17].

A recent study by Joppa [31], original in its manner of treating wall corrections in a guided test section, consisting in the sectioning of walls into uniform polygons containing layers of vortices, has been found to supplement and confirm [17] and [30].

3.4.4

Indeed, two values of l: l_a and l_e should be used (Figure 7) since they allow, on one hand, the application of corrections for incidence and pitch moment of airfoil and, on the other hand, corrections for pitch moment of the complete model using the horizontal stabilizer.

These corrections require, as will be seen below, the knowledge, in some cases, of the lift gradient of the airfoil in the presence of the fuselage and knowledge of the lift gradient of the horizontal stabilizer.

Knowledge of these gradients therefore implies supplementary testing.

For example, there should be made, parallel to each configuration of aircraft model, a test without horizontal stabilizer. The machine program then allows, in the case of each incidence, the calculation of $(dCz/di)_a$ and its placing in memory for the purpose of its later use for the corresponding test of complete model. /66

In practice, it can be seen that it is possible to reduce the number of tests without stabilizer to several type tests which can be used for the whole testing program of the stabilizer aircraft model.

3.4.5

Experimental data allowing knowledge of the aerodynamic operation of the horizontal stabilizer of an aircraft model placed in a wind tunnel are:

The dynamic pressure q_e of the air at right angles of this stabilizer taken with respect to the true and corrected dynamic pressure q_c of the blockage.

Its lift gradient $(dCz/di)_e$, the stabilizer being considered in its entirety, including the part in the fuselage. The angle of incidence at right angles to the stabilizer is not under consideration, the only factor is the angle induced by the walls and this angle is calculated as has been seen above.

The loss of lift undergone by the stabilizer may be separated into two parts: one coming—in case of certain aircraft configurations—from the screened surface inside the fuselage, and the other coming from the interaction produced by the latter.

3.4.6

In the absence of measurements, the search for the value of $(\frac{dCz}{di})_e$ can be accomplished by calculations.

It is true that Polhamus (NACA T.N. 3911) and Diederich (NACA T.N. 2335), proposed relations allowing the calculation of the airfoil lift gradient, including any plane shape whatsoever as a function of the streamlining, sweepback or elongation.

Now, a stabilizer possesses reduced dimensions with respect to those of an airfoil.

In this way, a stabilizer model is characterized at the present time not only by a slight elongation and a pronounced sweepback, but also by a rather low Reynolds number, often less than 1.10^6 which conditions its aerodynamic operation.

In the case of a stabilizer considered as an elongation airfoil λe and characterized by a sweepback $\phi 25\%$[4], we have used the following theoretical relation:

$$\frac{dCz}{di} \cong 2\pi . \frac{\lambda e}{\lambda e + 2} \cdot \cos \varphi_{25\%}$$

This relation, originated by Ringleb (NACA T.M. 1158), confirmed, in the case of low Reynold's numbers, in NACA T.N. 1278, has been taken under study and analyzed by John J. Harper (NACA T.N. 2495).

$2\pi\frac{\lambda}{\lambda + 2}$ is nothing more than the theoretical value of the lift gradient of a straight elliptical wing with elongation λ calculated by Glauert beginning

[4] Sweepback of the line joining the quarter point of the chords.

from the Prandtl theory, and whence 2π is the theoretical slope of the unit curve of lift of a fin profile with infinite elongation. This theoretical value is found theoretically reduced by approximately 10% enabling the following, expressed in degrees, to be written:

$$\frac{dCz}{di^{\circ}} \cong 0{,}1 \cdot \frac{\lambda e}{\lambda e + 2} \cdot \cos \varphi_{25\%}$$

Taking into account the loss of lift k = Czf + e/Cze owing to the presence of the fuselage, it is possible on an approximative basis to determine beginning from the study of Spreiter (NACA T.R. 962, p. 7) and from the reduction of dynamic pressure qe/qc (on the order of 2 to 3%), there will finally be produced:

$$\frac{qe}{qc}\left(\frac{dCz}{di^{\circ}}\right)_{e} = k\,\frac{qe}{qc} \cdot \frac{dCz}{di^{\circ}} \cong 0{,}08\,\frac{\lambda e}{\lambda e + 2} \cdot \cos \varphi_{25\%}$$

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